

ENERGY BALANCE CONSIDERATION IN PERMAFROST
HYDROLOGY

BY

G.P. WILLIAMS

Workshop Seminar on Permafrost,
CNC/IHD Calgary, Alberta
Feb. 26-28, 1974

Pam: 551.345
WIL

Pam:
WIL

POLAR
PAM
2276

POLARPAM

Subsurface Waters Session

ENERGY BALANCE CONSIDERATIONS IN PERMAFROST HYDROLOGY

G.P. Williams

Abstract

This general paper will attempt to show how surface heat exchange processes affect the movement and supply of water in permafrost regions. It will deal with several hydrological problem areas from an energy balance point of view. These include:- snow cover and snow melt, evaporation and evapotranspiration losses, and the hydrological significance of surface features (thermokarst, icings, etc.) which are partly determined by energy exchange processes. The paper will not go into detail or present new information but will be an "overview" of the general subject matter.

Résumé

Le but du présent document général est de montrer comment les processus d'échange de chaleur en surface touchent le mouvement de l'eau ainsi que l'approvisionnement en eau dans les régions de pergélisol. On y traite également de plusieurs problèmes hydrologiques, du point de vue de l'équilibre énergétique (couche de neige et la fonte de la neige, pertes par évaporation et évapotranspiration) et l'importance hydrologique des phénomènes superficiels comme le pseudo-karst, la glaciation, etc., qui sont en partie déterminés par les processus d'échange énergétique. On n'a pas l'intention d'aller dans le détail pour de fournir de nouveaux renseignements, mais plutôt de donner une vue d'ensemble du sujet.

BOREAL INSTITUTE

LIBRARY

OCT 4 1974

Rec'd:

Order No.

Price \$11.00
Acc No

17891

-3-

EXTENDED SUMMARY FOR
PERMAFROST HYDROLOGY SYMPOSIUM

ENERGY BALANCE CONSIDERATIONS IN
PERMAFROST HYDROLOGY

by

G. P. Williams

The subject of this paper is one which involves many aspects of permafrost study, dealing, as it does, with the thermal and moisture regime of the active layer. For example, almost every paper of the 86 papers from North America presented at the Second International Conference on Permafrost held at Yakutsk, U.S.S.R. in July 1973, deals directly or indirectly with some aspect of the inter-relation between surface heat exchange, the freezing and thawing of ground and the occurrence of water in its frozen or unfrozen state. One of the papers presented is a comprehensive review of the thermal aspects of permafrost formation and evaluation (Gold and Lachenbruch,

1973). An "overview" paper can thus only summarize a few of the highlights from these and many other papers in the literature concerned with this broad subject.

The paper is divided into three sections. The first part provides some general background information on surface energy exchange processes, particularly in permafrost regions; the second outlines some general hydrology problems in which surface heat exchange processes play a major role; and the third, dealing with the effect of terrain on surface heat exchange, is directed toward hydrologists who may not be familiar with the role of the surface cover in controlling the thawing and freezing of ground in permafrost regions.

SURFACE ENERGY EXCHANGE

The partitioning of heat received at the ground surface can be expressed by the following simplified heat balance equation:-

$$Q_s = I(1-a) + Q_{lw} + Q_c + Q_e$$

where I is the global solar radiation (direct plus diffuse); a the albedo (reflectivity of surface for solar radiation); Q_{lw} the net long-wave radiation (downward atmospheric less upward terrestrial); Q_c the convective (sensible) heat loss or gain; Q_e the evaporative heat loss or the heat gain by condensation; and Q_s the heat transferred to or from the

1973). An "overview" paper can thus only summarize a few of the highlights from these and many other papers in the literature concerned with this broad subject.

The paper is divided into three sections. The first part

gives some general background information on surface energy ex-

change processes, particularly in particulate regions; the second out-

lines some general hydrodynamic problems in which surface heat exchange

processes play a major role; and the third, dealing with the effect of

surface heat exchange, is directed toward hydrodynamic prob-

Digitized by the Internet Archive
in 2022 with funding from
University of Alberta Library

SURFACE ENERGY EXCHANGE

The partitioning of heat received at the ground surface

can be expressed by the following simplified heat balance equation:

$$Q_g = (1 - \alpha) Q_{lw} - Q_c - Q_e$$

where Q_g is the global solar radiation (W m⁻²), α is the albedo

(reflectivity of surface for solar radiation), Q_{lw} the net long-wave

radiation (downward atmospheric long-wave radiation), Q_c the con-

vective (sensible) heat loss in W m⁻², Q_e the evaporative heat loss at the

heat gain by condensation, and Q_s the heat transferred to or from the

ground. The heat used in photosynthesis, included in Q_s , is a significant factor in surface heat exchange only during fire, which releases the energy stored during several seasons by photosynthesis.

The different terms in the surface heat balance equation can be calculated on a "climatological" basis. The accuracy of such calculations is often not high as they depend not only on meteorological parameters which are subject to time and space variations but also on highly variable surface characteristics. Table I, listing the variables that influence each term, shows that global solar radiation (I) is the only term that does not depend on surface characteristics.

TABLE I

Variables that influence various
terms in Surface Energy Exchange

<u>Term</u>	<u>Variables</u>
I	latitude, time of year, type of air mass, elevation, per cent cloud cover
a	surface characteristics, altitude of sun
Q_{lw}	surface and air temperatures, emissivity of earth surface and sky, cloud type, per cent cloud cover, height of cloud
Q_c	surface and air temperatures, wind speed, stability of air, surface roughness
Q_e	wind speed, surface roughness, soil moisture, type of vegetation
Q_s	thermal and moisture properties of the ground cover

The heat lost or gained by the ground surface is of special significance in the long term growth or degradation of permafrost. To quote one authority (Lachenbruch 1968):- "If a secular change in surface conditions causes the mean annual ground surface temperature to drop below 0°C , the depth of freezing in winter will exceed the depth of thawing in summer, and a layer of permafrost will grow downward from the base of the seasonal frost. It will thicken progressively with the passage of each succeeding winter. Were it not for the effect of heat escaping from the earth's interior, the permafrost would grow to great depths." The small amount of heat flow from the earth's interior, estimated to be only about $50 \text{ cal/cm}^2/\text{yr}$, (Millar, 1965), or less than the heat required to melt a gram of ice, puts into perspective the delicate thermal balance of permafrost and how very small annual changes in surface heat exchange over a period of many years can affect the permafrost condition.

Hydrologists are more interested in the short term effects of surface heat exchange. The heat gained during the summer determines the depth of thaw and thus the availability of water in the active layer above the permafrost. The heat lost during the winter determines the rapidity with which surface layers freeze; it also determines the thickness of ice on lakes and rivers which affects winter runoff.

Heat losses and gains to ground surfaces are much less than other terms in the surface heat exchange. For example, during the thaw season the total heat flow into the ground is usually less than 10 per cent of the net radiation received at the surface. It is thus difficult to determine Q_s , with any degree of accuracy, by calculating or measuring the components on the right hand side of the heat balance equation. Also, as the components of the surface heat exchange vary greatly over an area the size of a watershed because of different surface covers, it is not possible to use only one instrumented site to measure components that will be representative of the entire area (Wendler and Ishikawa, 1973).

HYDROLOGY PROBLEMS AND SURFACE HEAT EXCHANGE

In general, hydrology problems fall into two classes:-

(1) problems dealing with water and heat balances on a large scale and
(2) problems concerned with surface runoff of groundwater at a site or specific watershed. It is beyond the scope of this paper to consider large scale or macroscale problems other than to indicate there has been considerable interest in them in permafrost regions. Recent studies (Dingman, 1973; Hare and Hay, 1971) of annual balances over northern North America provide much information which would be of

interest for anyone concerned with the hydrology of permafrost regions.

Some of the smaller scale hydrology problems which require at least a knowledge of the surface heat exchange and in many cases require an estimate of one or more of the terms in the heat balance equation can be listed as follows:-

1. Predicting the effect of ice on surface and groundwater runoff in winter;
2. Predicting annual snow melt runoff; calculating snow melt design floods.
3. Estimating evaporation losses from reservoirs or evapotranspiration losses from watersheds.
4. Predicting summer runoff in rivers, including infiltration losses over watersheds.
5. Predicting available groundwater supplies.
6. Designing drainage systems and controlling erosion.

These hydrology problems and often the methods of solving them are similar in permafrost as in non-permafrost regions but some important differences do exist.

For example, in permafrost regions, the common occurrence of icings complicates the prediction and control of winter

runoff. The term icing is used to describe a mass of surface ice formed primarily by successive freezing of groundwater which continues to flow to the surface of the ground or a river ice cover during the winter. Problems arise when the paths of water movement become blocked leading to an accumulated mass of surface ice, resulting in obstructed drainage channels and an aggravation of the spring season flood stage. The prediction of the occurrence of icings is difficult depending on many different factors such as climate, hydrology, geology and topography (Carey, 1973).

The problem of estimating snow melt runoff is complicated by the presence of permafrost as it can control the amount of snow melt that will percolate into the soil. In the discontinuous zone permafrost may occur on north-facing slopes but not on adjacent south-facing slopes; in the continuous zone, permafrost is often thicker and the active layer thinner on north-facing slopes (Brown and Péwé, 1973). These differences in underlying permafrost conditions, often marked by differences in vegetative cover, affect the rate of snow melt runoff and should be considered in any method developed to predict snow melt runoff from watersheds with different slopes of varying orientation. A characteristic of snow melt in tundra is the rapid change in the amount of solar radiation absorbed by the surface as the snow melts

and the underlying surface cover becomes exposed to the high amounts of incoming solar radiation (Weller, 1972, McFadden and Ragotzkie, 1967). Melting is less rapid in the boreal forest region because of the sheltering effect of the tree cover.

The basic problem of estimating evaporation from water surfaces is the same for permafrost regions as elsewhere. Mass-transfer or energy balance formulae can be used, the limiting factor usually being the availability of adequate meteorological records. The estimation of evapotranspiration losses from watersheds presents some additional problems because extensive areas are covered with peatland which influences the availability of water for evaporation.

Hydrology problems involving surface heat exchange during the thaw period such as estimating the runoff from rainfall, infiltration, the movement of groundwater and the erosion of drainage channels are profoundly influenced by the presence of permafrost. The complexity of the relationships between meteorological variables, surface covers and depth of thaw makes it extremely difficult to obtain quantitative values for many of the parameters such as infiltration and permeability, which are needed to solve hydrological problems using classical approaches. The creation of unusual terrain features, such as thermokarst topography or patterned ground, by the thawing of permafrost adds to the

complications. The role of the land in controlling surface runoff and groundwater flow has been extensively studied in non-permafrost areas; in permafrost regions only a few, limited studies have been made even though the major difference between the hydrology of permafrost and non-permafrost areas is clearly the effects of frozen ground and the resulting terrain features on the movement and supply of water.

SURFACE COVER - ENERGY EXCHANGE - PERMAFROST HYDROLOGY

Permafrost terrain presents a variegated mosaic of surface covers, each with special thermal and surface properties. In this section some of these properties are considered in relation to surface energy exchange to give a qualitative understanding of how they influence permafrost hydrology.

The principal surface properties that affect the heat exchange are albedo, emissivity and surface roughness. Of these, albedo, controlling the solar radiation absorbed, is of greatest importance. Albedo of surface covers vary from a high of 80 per cent or greater for new snow to a low of 10 per cent or less for water. The emissivity, controlling the amount of long-wave radiation emitted, is not greatly variable for most natural surfaces. The surface roughness, of importance in convective and evaporative heat transfer processes, is

highly variable but it is beyond the scope of this paper to discuss the complex effect of surface roughness on these processes (Priestley, 1959).

The thermal properties that control heat flow through various surface covers are volumetric heat capacity (C_v), latent heat of fusion and thermal conductivity (k). The product $\sqrt{kC_v}$, termed the conductive capacity, has a critical role in determining the amount of heat transferred into the earth's surface from the atmosphere. Representative values of conductive capacity of some surface covers, listed in Table II, provide an appreciation of the ability of natural materials to respond or adjust to imposed temperature changes. New snow or dry sphagnum moss, for example, offer a much higher resistance to change than turbulent water. Not only does the conductive capacity of the surface cover have a great influence on the thermal response of the ground but it also affects the ability of a particular surface type to thermally modify the air above it.

TABLE II

Representative values for conductive capacity
of natural covers

(Priestley, C. H. B., 1969, Williams, G. P., 1968)

	conductive capacity (cal/cm ² °C sec ^{$\frac{1}{2}$}) x 1000
Snow fresh	2
old	10-15
Dry sphagnum moss	1-2
Sand dry	10
wet	40
Peat unfrozen	20-40
frozen	25-50
Ice	50
Water stable	300
moderately stable	7000
unstable, strong currents	17000

Of all surface covers, water has probably the most significant effect on permafrost. The low albedo of water results in high absorption of short-wave radiation. The high thermal capacity of water and the ease with which water bodies undergo turbulent mixing means that large amounts of heat can be stored in them during summer. The ice cover that forms in winter acts as an insulating layer, preventing

excessive heat loss. If a water body is sufficiently deep, water will remain unfrozen and the mean annual temperature of the ground beneath it can be several degrees above freezing even in permafrost regions. The thawed zone under water bodies and the thawing action of water moving through thaw zones is not only of hydrological significance but can be a significant factor in the design of engineering structures.

Snow cover can be a critical factor in the formation and existence of permafrost, particularly in the southern fringe of the discontinuous permafrost zone. During winter, its low conductive capacity and low thermal conductivity inhibit the freezing of ground. During the spring period, the high albedo reduces the amount of solar radiation absorbed, resulting in delayed melting of the ground. The relation between these two conflicting situations determines the net effect of snow cover on the ground thermal regime. The hydrological significance of snow covers is even greater than it is in areas of seasonal frost because of its control on the depth of thaw and presence of permafrost and hence groundwater movement and infiltration rates throughout the entire thaw season.

Peat, a common form of surface cover in permafrost regions, has some unique features which influence the occurrence of ice in the ground. The latent heat of fusion of saturated peat is usually

much higher than that of mineral soils; and the thermal conductivity lower. Consequently the rate of frost penetration and of thawing is much slower in peat than mineral soils exposed to the same weather conditions. The micro-relief present in the form of peat mounds, ridges and plateaux as well as the living vegetation, consisting primarily of mosses, lichens and sedges, also influence ground temperatures, the occurrence of ice in the ground and the soil moisture regime. In saturated peat most of the heat available from solar radiation is expended in evaporation and is not available to warm the soil. In contrast, evaporation can be greatly reduced if lichen is the vegetative surface cover, (Rouse and Stewart, 1972).

The role of other surface covers, such as the boreal forest, in controlling surface heat exchange is most complex, affecting every term in the heat balance equation as well as soil moisture and snow depth and snow distribution (Hare and Ritchie, 1972).

CONCLUDING DISCUSSION

Almost every change man makes to natural terrain in permafrost regions will change surface heat exchange and the thermal and moisture regime of the ground. It is not surprising, therefore, that attempts have been made to control these changes to benefit

engineering works. In many cases surface modifications have been designed to prevent thawing of the ground and thus preserve the permafrost; in other cases the depth of thaw is deliberately increased to facilitate mining operations (Bakakin and Porkhaev, 1966). There is, however, not much published information on how man might modify surface covers to benefit hydrology problems such as controlling or increasing the supply of water. As a closing discussion it is worthwhile to mention briefly some of the possibilities.

One example might be the use of snow fences to conserve and collect snow to increase snow melt runoff. The snow accumulated by snow fences will not only inhibit the freezing of the ground but also make more snow available for runoff. During the spring melt period it might be advantageous to pile the accumulated snow in windrows by bulldozers, exposing the ground, so that the melting of the frozen ground is not delayed because of the deep snow cover. Another method of increasing the rate at which the snow will melt would be to dust the surface of the snow with a suitable material (Williams and Gold, 1963).

Other examples might be the deliberate flooding or the removal of vegetative covers from suitable areas to increase the depth of thaw and thus increase groundwater storage. Plans for flooding or the stripping of ground covers must also take into account the effects

on evaporation, depth of freezing and the distribution and depth of snow in winter, as any change made to surface covers will affect the thermal balance throughout the entire year. The difficulty of controlling one term in the heat balance equation without affecting another imposes a certain practical limit on the benefits that can be obtained by the modification of surface covers.

In conclusion it can be said that a potential exists to modify surface covers so as to control water in permafrost regions where water supply is limited. Well planned experiments are needed, taking into account the cost benefits as well as all the factors that influence surface thermal and moisture regimes in permafrost regions.

REFERENCES

- Bakakin, V. P. and Porkhaev, G. V. Principal methods of moisture-thermal amelioration of the ground over large areas. Chapter V, Principles of Geocryology, NRC TT 1250, 1966.
- Brown, R. J. E. and Péwé, T. L. Distribution of permafrost in North America and its relationship to the environment: A review 1963-1973. North American Contributions to Second International Conference on Permafrost, Yakutsk, U.S.S.R., July 1973.
- Carey, Kevin L. Icings developed from surface water and ground water. CRREL Monograph 111-D3, U.S. Corps of Engineers, Hanover, N.H., May 1973.
- Dingman, S. L. The water balance in Arctic and Subarctic regions. CRREL Special Report 187, U.S. Corps of Engineers, Hanover, N.H., June 1973.
- Gold, L. W. and Lachenbruch, A. H. A review of North American literature. North American contribution to Second International Conference on Permafrost, Yakutsk, U.S.S.R., July 1973.
- Hare, F. K. and Hay, J. E. Anomalies in the large-scale annual water balance over northern North America. Canadian Geographer XV, 2, 1971.
- Hare, F. K. and Ritchie, J. C. The boreal bioclimates. The Geographical Review, The American Geographical Society of New York, July 1972.
- Lachenbruch, A. H. Permafrost. The Encyclopedia of Geomorphology, R. W. Fairbridge, Reinhold, pp. 833-839, 1968.
- Millar, D. H. The heat and water budget of the earth's surface. Advances in Geophysics 11, pp. 175-302, 1965.
- McFadden, J. D. and Ragotzkie, R. A. Climatological significance of albedo in central Canada. J. of Geophysical Research, Vol. 72, No. 4, 15 February 1967.

- Priestley, C. H. B. Turbulent transfer in the lower atmosphere. The University of Chicago Press, Chicago, 1959.
- Rouse, W. R. and Stewart, R. B. A simple method for determining evaporation from high-latitude upland sites. J. of Applied Meteorology, October 1972.
- Weller, G. et al. The tundra microclimate during snow-melt at Barrow, Alaska. Arctic, Vol. 25, No. 4, December 1972.
- Wendler, G. and Ishikawa, N. Heat balance investigation in an Arctic mountainous area in northern Alaska. J. of App. Meteorology, Vol. 12, No. 6, September 1973.
- Williams, G. P. The thermal regime of a sphagnum peat bog. Proceedings of 3rd International Peat Congress, Quebec, pp. 195-200, August 1968.
- Williams, G. P. and Gold, L. W. The use of dust to advance the break-up of ice on lakes and rivers. Proceedings of the Eastern Snow Conference, p. 31-56, 1963.

Date Due

NOV 10 '75

1930

MAR 27 1978

NOV 15 RETURN

17891

BOREAL INSTITUTE
FOR NORTHERN STUDIES LIBRARY
THE UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA. T6G 2E9

University of Alberta Library



0 1620 0332 8471